Administrivia

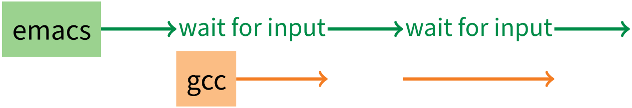
- **Section Friday 1pm-1:50pm, same zoom link as lecture**
  - Please attend first section this Friday to learn about lab 1
- **Lab 1 due Friday, Jan 29 at 12pm**
- **Ask `cs140-staff` for extension if you can't finish**
  - Tell us where you are with the project,
  - How much more you need to do, and
  - How much longer you need to finish
- **No credit for late assignments w/o extension**
- **You can do projects in a solo group, but I don't recommend it**
  - Extra work for no additional credit
  - Plus you'll be missing out on one aspect of the class
- **Reminder: find partners at 6pm today in Nooks**

Processes

- **A *process* is an instance of a program running**
- **Modern OSes run multiple processes simultaneously**
- **Examples (can all run simultaneously):**
  - `gcc file_A.c` – compiler running on file A
  - `gcc file_B.c` – compiler running on file B
  - `emacs` – text editor
  - `firefox` – web browser
- **Non-examples (implemented as one process):**
  - Multiple firefox windows or emacs frames (still one process)
- **Why processes?**
  - Simplicity of programming
  - Speed: Higher throughput, lower latency

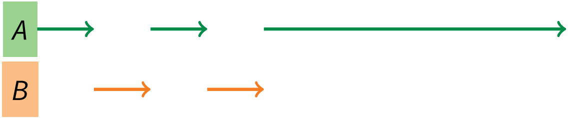
Speed

- **Multiple processes can increase CPU utilization**
  - Overlap one process's computation with another's wait



- **Multiple processes can reduce latency**
  - Running *A* then *B* requires 100 sec for *B* to complete

  - Running *A* and *B* concurrently makes *B* finish faster



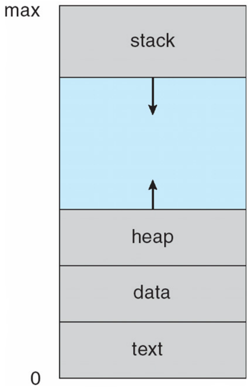
  - *A* is slower than if it had whole machine to itself, but still $<$ 100 sec unless both *A* and *B* completely CPU-bound

Processes in the real world

- **Processes and parallelism have been a fact of life much longer than OSes have been around**
  - E.g., say takes 1 worker 10 months to make 1 widget
  - Company may hire 100 workers to make 100 widgets
  - Latency for first widget $\gg 1/10$ month
  - Throughput may be < 10 widgets per month (if can't perfectly parallelize task)
  - And 100 workers making 10,000 widgets may achieve > 10 widgets/month (e.g., if workers never idly wait for paint to dry)
- **You will see these effects in you Pintos project group**
  - May block waiting for partner to complete task
  - Takes time to coordinate/explain/understand one another's code
  - Labs won't take $1/3$ time with three people
  - But you will graduate faster than if you took only 1 class at a time

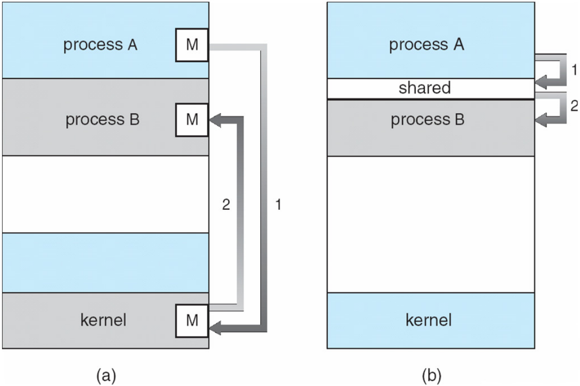
A process's view of the world

- **Each process has own view of machine**
  - Its own address space – `*(char *)0xc000` different in P_1 & P_2
  - Its own open files
  - Its own virtual CPU (through preemptive multitasking)
- **Simplifies programming model**
  - `gcc` does not care that `firefox` is running



- **Sometimes want interaction between processes**
  - Simplest is through files: `emacs` edits file, `gcc` compiles it
  - More complicated: Shell/command, Window manager/app.

Inter-Process Communication



- **How can processes interact in real time?**
  (a) By passing messages through the kernel
  (b) By sharing a region of physical memory
  (c) Through asynchronous signals or alerts

Outline

Creating processes

- **Original UNIX paper is a great reference on core system calls**
- `int fork (void);`
  - Create new process that is exact copy of current one
  - Returns *process ID* of new process in “parent”
  - Returns 0 in “child”
- `int waitpid (int pid, int *stat, int opt);`
  - `pid` – process to wait for, or -1 for any
  - `stat` – will contain exit value, or signal
  - `opt` – usually 0 or `WNOHANG`
  - Returns process ID or -1 on error

Deleting processes

- `void exit (int status);`
  - Current process ceases to exist
  - `status` shows up in `waitpid` (shifted)
  - By convention, `status` of 0 is success, non-zero error
- `int kill (int pid, int sig);`
  - Sends signal `sig` to process `pid`
  - `SIGTERM` most common value, kills process by default (but application can catch it for “cleanup”)
  - `SIGKILL` stronger, kills process always

Running programs

- `int execve (char *prog, char **argv, char **envp);`
  - `prog` – full pathname of program to run
  - `argv` – argument vector that gets passed to `main`
  - `envp` – environment variables, e.g., `PATH`, `HOME`
- **Generally called through a wrapper functions**
  - `int execvp (char *prog, char **argv);`
    Search `PATH` for prog, use current environment
  - `int execlp (char *prog, char *arg, ...);`
    List arguments one at a time, finish with `NULL`
- **Example:** `minish.c`
  - Loop that reads a command, then executes it
- **Warning: Pintos `exec` more like combined fork/exec**

minish.c (simplified)

```
pid_t pid; char **av;
void doexec () {
  execvp (av[0], av);
  perror (av[0]);
  exit (1);
}

    /* ... main loop: */
    for (;;) {
      parse_next_line_of_input (&av, stdin);
      switch (pid = fork ()) {
      case -1:
        perror ("fork"); break;
      case 0:
        doexec ();
      default:
        waitpid (pid, NULL, 0); break;
      }
    }
```

Manipulating file descriptors

- `int dup2 (int oldfd, int newfd);`
  - Closes `newfd`, if it was a valid descriptor
  - Makes `newfd` an exact copy of `oldfd`
  - Two file descriptors will share same offset
    (`lseek` on one will affect both)
- `int fcntl (int fd, int cmd, ...)` – **misc fd configuration**
  - `fcntl (fd, F_SETFD, val)` – sets close-on-exec flag
    When `val == 0`, `fd` not inherited by spawned programs
  - `fcntl (fd, F_GETFL)` – get misc fd flags
  - `fcntl (fd, F_SETFL, val)` – set misc fd flags
- **Example:** `redirsh.c`
  - Loop that reads a command and executes it
  - Recognizes `command < input > output 2> errlog`

redirsh.c

```
void doexec (void) {
  int fd;
  if (infile) {     /* non-NULL for "command < infile" */
    if ((fd = open (infile, O_RDONLY)) < 0) {
      perror (infile);
      exit (1);
    }
    if (fd != 0) {
      dup2 (fd, 0);
      close (fd);
    }
  }

  /* ... do same for outfile→fd 1, errfile→fd 2 ... */

  execvp (av[0], av);
  perror (av[0]);
  exit (1);
}
```

Pipes

- `int pipe (int fds[2]);`
  - Returns two file descriptors in `fds[0]` and `fds[1]`
  - Data written to `fds[1]` will be returned by `read` on `fds[0]`
  - When last copy of `fds[1]` closed, `fds[0]` will return EOF
  - Returns 0 on success, -1 on error
- **Operations on pipes**
  - `read`/`write`/`close` – as with files
  - When `fds[1]` closed, `read(fds[0])` returns 0 bytes
  - When `fds[0]` closed, `write(fds[1])`:
    - ▷ Kills process with `SIGPIPE`
    - ▷ Or if signal ignored, fails with EPIPE
- **Example:** `pipesh.c`
  - Sets up pipeline `command1 | command2 | command3 ...`

pipesh.c (simplified)

```
void doexec (void) {
  while (outcmd) {
    int pipefds[2]; pipe (pipefds);
    switch (fork ()) {
    case -1:
      perror ("fork"); exit (1);
    case 0:
      dup2 (pipefds[1], 1);
      close (pipefds[0]); close (pipefds[1]);
      outcmd = NULL;
      break;
    default:
      dup2 (pipefds[0], 0);
      close (pipefds[0]); close (pipefds[1]);
      parse_command_line (&av, &outcmd, outcmd);
      break;
    }
  }
  ⋮
```

Multiple file descriptors

- **What if you have multiple pipes to multiple processes?**
- **`poll` system call lets you know which fd you can read/write**[1]

```
typedef struct pollfd {
  int fd;
  short events;   // OR of POLLIN, POLLOUT, POLLERR, ...
  short revents;  // ready events returned by kernel
};
int poll(struct pollfd *pfds, int nfds, int timeout);
```

- **Also put pipes/sockets into *non-blocking* mode**

```
  if ((n = fcntl (s.fd_, F_GETFL)) == -1
      || fcntl (s.fd_, F_SETFL, n | O_NONBLOCK) == -1)
    perror("O_NONBLOCK");
```

  - Returns errno `EGAIN` instead of waiting for data
  - Does not work for normal files (see aio for that)

[1] In practice, more efficient to use `epoll` on linux or `kqueue` on *BSD

Why fork?

- **Most calls to `fork` followed by `execve`**
- **Could also combine into one *spawn* system call (like Pintos `exec`)**
- **Occasionally useful to fork one process**
  - Unix *dump* utility backs up file system to tape
  - If tape fills up, must restart at some logical point
  - Implemented by forking to revert to old state if tape ends
- **Real win is simplicity of interface**
  - Tons of things you might want to do to child: Manipulate file descriptors, alter namespace, manipulate process limits . . .
  - Yet `fork` requires *no* arguments at all

Examples

- `login` – **checks username/password, runs user shell**
  - Runs with administrative privileges
  - Lowers privileges to user before exec'ing shell
  - Note doesn't need `fork` to run shell, just `execve`
- `chroot` – **change root directory**
  - Useful for setting/debugging different OS image in a subdirectory
- **Some more linux-specific examples**
  - `systemd-nspawn` – runs program in container-like environment
  - `ip netns` – runs program with different network namespace
  - `unshare` – decouple namespaces from parent and exec program

Spawning a process without fork

- **Without fork, needs tons of different options for new process**
- **Example: Windows `CreateProcess` system call**
  - Also `CreateProcessAsUser`, `CreateProcessWithLogonW`, `CreateProcessWithTokenW`, ...

```
BOOL WINAPI CreateProcess(
  _In_opt_      LPCTSTR lpApplicationName,
  _Inout_opt_   LPTSTR lpCommandLine,
  _In_opt_      LPSECURITY_ATTRIBUTES lpProcessAttributes,
  _In_opt_      LPSECURITY_ATTRIBUTES lpThreadAttributes,
  _In_          BOOL bInheritHandles,
  _In_          DWORD dwCreationFlags,
  _In_opt_      LPVOID lpEnvironment,
  _In_opt_      LPCTSTR lpCurrentDirectory,
  _In_          LPSTARTUPINFO lpStartupInfo,
  _Out_         LPPROCESS_INFORMATION lpProcessInformation
);
```

Outline

1. (UNIX-centric) User view of processes
2. Kernel view of processes
3. Threads
4. Thread implementation details

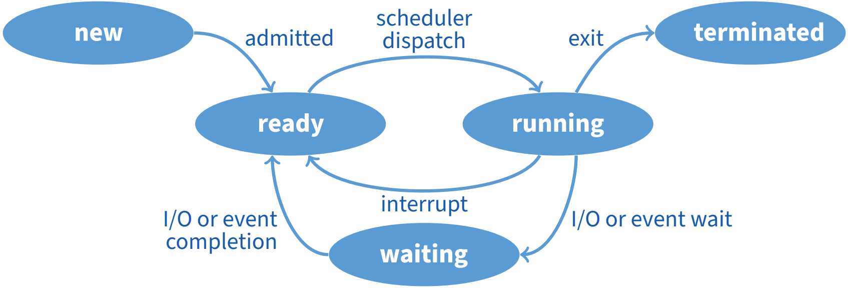
Implementing processes

- **Keep a data structure for each process**
  - Process Control Block (PCB)
  - Called `proc` in Unix, `task_struct` in Linux, and just `struct thread` in Pintos
- **Tracks *state* of the process**
  - Running, ready (runnable), waiting, etc.
- **Includes information necessary to run**
  - Registers, virtual memory mappings, etc.
  - Open files (including memory mapped files)
- **Various other data about the process**
  - Credentials (user/group ID), signal mask, controlling terminal, priority, accounting statistics, whether being debugged, which system call binary emulation in use, . . .

Process state
Process ID
User id, etc.
Program counter
Registers
Address space (VM data structs)
Open files

PCB

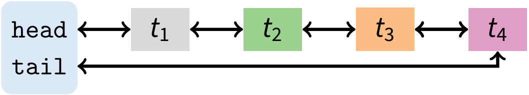
Process states



- **Process can be in one of several states**
  - *new* & *terminated* at beginning & end of life
  - *running* – currently executing (or will execute on kernel return)
  - *ready* – can run, but kernel has chosen different process to run
  - *waiting* – needs async event (e.g., disk operation) to proceed
- **Which process should kernel run?**
  - if 0 runnable, run idle loop (or halt CPU), if 1 runnable, run it
  - if $>$1 runnable, must make scheduling decision

Scheduling

- **How to pick which process to run**
- **Scan process table for first runnable?**
  - Expensive. Weird priorities (small pids do better)
  - Divide into runnable and blocked processes
- **FIFO?**
  - Put threads on back of list, pull them from front:



  - Pintos does this—see `ready_list` in `thread.c`
- **Priority?**
  - Give some threads a better shot at the CPU

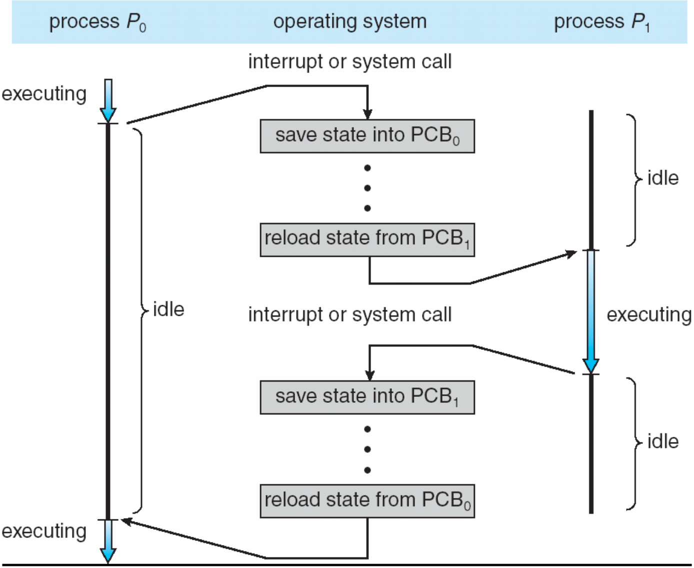
Scheduling policy

- **Want to balance multiple goals**
  - *Fairness* – don't starve processes
  - *Priority* – reflect relative importance of procs
  - *Deadlines* – must do *X* (play audio) by certain time
  - *Throughput* – want good overall performance
  - *Efficiency* – minimize overhead of scheduler itself
- **No universal policy**
  - Many variables, can't optimize for all
  - Conflicting goals (e.g., throughput or priority vs. fairness)
- **We will spend two lectures on this topic**
  - One basic lecture, plus guest lecture at end of quarter

Preemption

- **Can preempt a process when kernel gets control**
- **Running process can vector control to kernel**
  - System call, page fault, illegal instruction, etc.
  - May put current process to sleep—e.g., read from disk
  - May make other process runnable—e.g., fork, write to pipe
- **Periodic timer interrupt**
  - If running process used up quantum, schedule another
- **Device interrupt**
  - Disk request completed, or packet arrived on network
  - Previously waiting process becomes runnable
  - Schedule if higher priority than current running proc.
- **Changing running process is called a *context switch***

Context switch

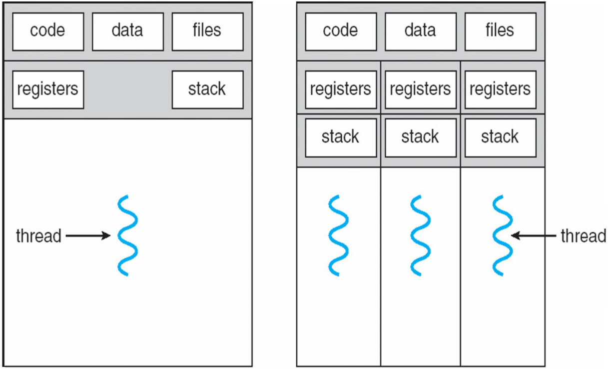


Context switch details

- **Very machine dependent. Typical things include:**
  - Save program counter and integer registers (always)
  - Save floating point or other special registers
  - Save condition codes
  - Change virtual address translations
- **Non-negligible cost**
  - Save/restore floating point registers expensive
    - Optimization: only save if process used floating point
  - May require flushing TLB (memory translation hardware)
    - HW Optimization 1: don't flush kernel's own data from TLB
    - HW Optimization 2: use tag to avoid flushing any data
  - Usually causes more cache misses (switch working sets)

Outline

Threads



single-threaded process   multithreaded process

- **A thread is a schedulable execution context**
  - Program counter, stack, registers, ...
- **Simple programs use one thread per process**
- **But can also have multi-threaded programs**
  - Multiple threads running in same process's address space

Why threads?

- **Most popular abstraction for concurrency**
  - Lighter-weight abstraction than processes
  - All threads in one process share memory, file descriptors, etc.
- **Allows one process to use multiple CPUs or cores**
- **Allows program to overlap I/O and computation**
  - Same benefit as OS running `emacs` & `gcc` simultaneously
  - E.g., threaded web server services clients simultaneously:

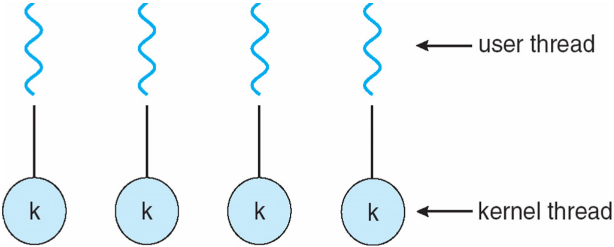
```
for (;;) {
  c = accept_client();
  thread_create(service_client, c);
}
```

- **Most kernels have threads, too**
  - Typically at least one kernel thread for every process
  - Switch kernel threads when preempting process

Thread package API

- `tid thread_create (void (*fn) (void *), void *);`
  - Create a new thread, run `fn` with `arg`
- `void thread_exit ();`
  - Destroy current thread
- `void thread_join (tid thread);`
  - Wait for thread `thread` to exit
- **Plus lots of support for synchronization [in 3 weeks]**
- **See [Birell] for good introduction**
- **Can have preemptive or non-preemptive threads**
  - Preemptive causes more race conditions
  - Non-preemptive can't take advantage of multiple CPUs
  - Before prevalence of multicore, most kernels non-preemptive

Kernel threads

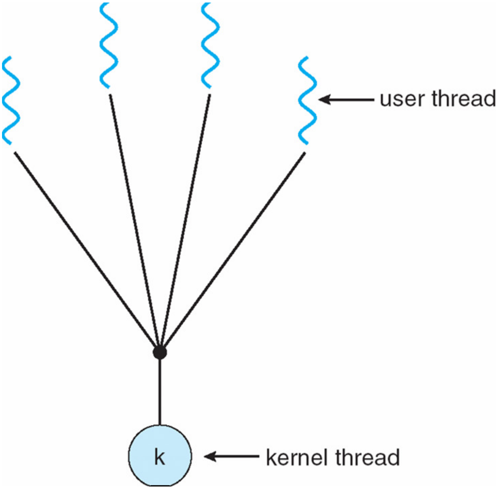


- **Can implement `thread_create` as a system call**
- **To add `thread_create` to an OS that doesn't have it:**
  - Start with process abstraction in kernel
  - `thread_create` like process creation with features stripped out
    - Keep same address space, file table, etc., in new process
    - `rfork`/`clone` syscalls actually allow individual control
- **Faster than a process, but still very heavy weight**

Limitations of kernel-level threads

- **Every thread operation must go through kernel**
  - create, exit, join, synchronize, or switch for any reason
  - On my laptop: syscall takes 100 cycles, fn call 5 cycles
  - Result: threads 10x-30x slower when implemented in kernel
- **One-size fits all thread implementation**
  - Kernel threads must please all people
  - Maybe pay for fancy features (priority, etc.) you don't need
- **General heavy-weight memory requirements**
  - E.g., requires a fixed-size stack within kernel
  - Other data structures designed for heavier-weight processes

Alternative: User threads



- **Implement as user-level library (a.k.a. *green* threads)**
  - One kernel thread per process
  - `thread_create`, `thread_exit`, etc., just library functions

Implementing user-level threads

- **Allocate a new stack for each** `thread_create`
- **Keep a queue of runnable threads**
- **Replace networking system calls (**`read`**/**`write`**/etc.)**
  - If operation would block, switch and run different thread
- **Schedule periodic timer signal (**`setitimer`**)**
  - Switch to another thread on timer signals (preemption)
- **Multi-threaded web server example**
  - Thread calls `read` to get data from remote web browser
  - “Fake” `read` *function* makes `read` *syscall* in non-blocking mode
  - No data? schedule another thread
  - On timer or when idle check which connections have new data

Outline

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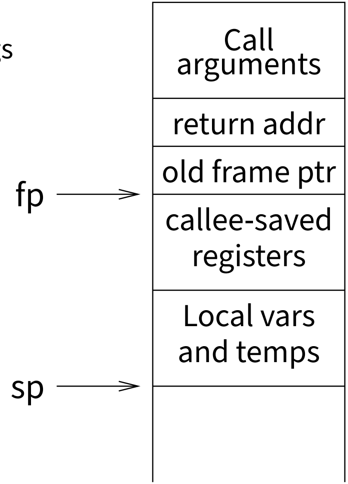
Background: calling conventions

- **Registers divided into 2 groups**
  - Functions free to clobber *caller-saved* regs (`%eax` [return val], `%edx`, & `%ecx` on x86)
  - But must restore *callee-saved* ones to original value upon return (on x86, `%ebx`, `%esi`, `%edi`, plus `%ebp` and `%esp`)
- ***sp* register always base of stack**
  - Frame pointer (*fp*) is old *sp*
- **Local variables stored in registers and on stack**
- **Function arguments go in caller-saved regs and on stack**
  - With 32-bit x86, all arguments on stack



Background: procedure calls

Procedure call

save active caller registers
push arguments to stack
call `foo` (pushes pc) →
 save needed callee registers
 ...do stuff...
 restore callee saved registers
 jump back to calling function
restore stack+caller regs. ←

- **Caller must save some state across function call**
  - Return address, caller-saved registers
- **Other state does not need to be saved**
  - Callee-saved regs, global variables, stack pointer

Pintos thread implementation

- **Pintos implements user processes on top of its own threads**
  - Same technique can be used to implement user-level threads, too
- **Per-thread state in thread control block structure**

```
struct thread {
    ...
    uint8_t *stack;  /* Saved stack pointer. */
    ...
};
uint32_t thread_stack_ofs = offsetof(struct thread, stack);
```

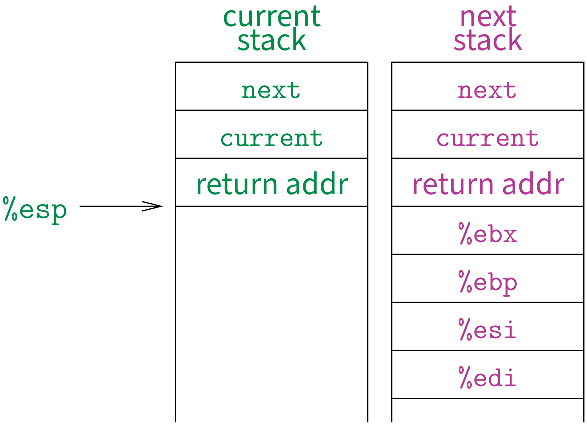
- **C declaration for asm thread-switch function:**
  - `struct thread *switch_threads (struct thread *cur,`
    `struct thread *next);`
- **Also thread initialization function to create new stack:**
  - `void thread_create (const char *name,`
    `thread_func *function, void *aux);`

i386 switch_threads

```
pushl %ebx; pushl %ebp              # Save callee-saved regs
pushl %esi; pushl %edi

mov thread_stack_ofs, %edx          # %edx = offset of stack field
                                    #        in thread struct

movl 20(%esp), %eax                 # %eax = cur
movl %esp, (%eax,%edx,1)            # cur->stack = %esp

movl 24(%esp), %ecx                 # %ecx = next
movl (%ecx,%edx,1), %esp            # %esp = next->stack

popl %edi; popl %esi                # Restore calle-saved regs
popl %ebp; popl %ebx

ret                                 # Resume execution
```

- **This is actual code from Pintos `switch.S` (slightly reformatted)**
  - See Thread Switching in documentation

i386 `switch_threads`



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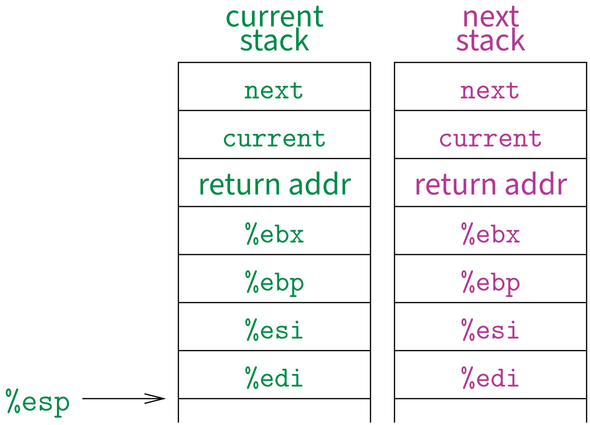

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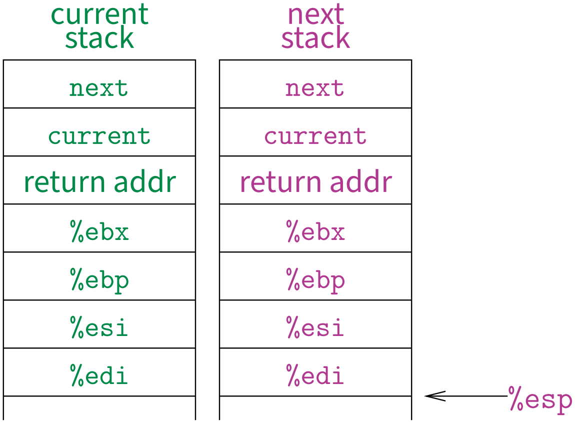

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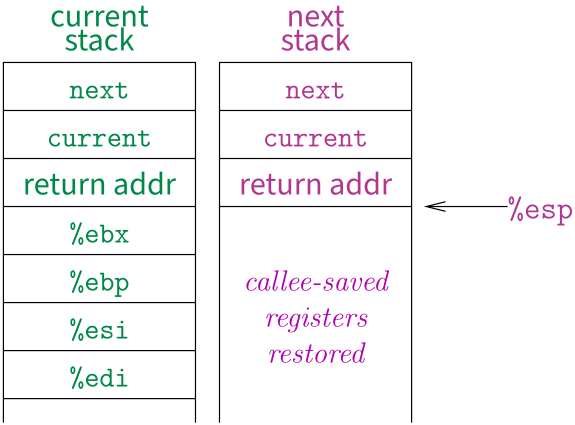
i386 switch_threads

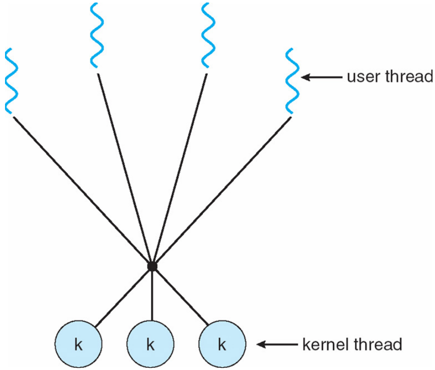


- **This is actual code from Pintos `switch.S` (slightly reformatted)**
  - See Thread Switching in documentation

Limitations of user-level threads

- **A user-level thread library can do the same thing as Pintos**
- **Can't take advantage of multiple CPUs or cores**
- **A blocking system call blocks all threads**
  - Can use `O_NONBLOCK` to avoid blocking on network connections
  - But doesn't work for disk (e.g., even aio doesn't work for metadata)
  - So one uncached disk read/synchronous write blocks all threads
- **A page fault blocks all threads**
- **Possible deadlock if one thread blocks on another**
  - May block entire process and make no progress
  - [More on deadlock in future lectures.]

User threads on kernel threads



- **User threads implemented on kernel threads**
  - Multiple kernel-level threads per process
  - `thread_create`, `thread_exit` still library functions as before
- **Sometimes called** $n : m$ **threading**
  - Have n user threads per m kernel threads
    (Simple user-level threads are $n : 1$, kernel threads $1 : 1$)

Limitations of $n : m$ threading

- **Many of same problems as $n : 1$ threads**
  - Blocked threads, deadlock, …
- **Hard to keep same # ktrheads as available CPUs**
  - Kernel knows how many CPUs available
  - Kernel knows which kernel-level threads are blocked
  - But tries to hide these things from applications for transparency
  - So user-level thread scheduler might think a thread is running while underlying kernel thread is blocked
- **Kernel doesn't know relative importance of threads**
  - Might preempt kthread in which library holds important lock

Lessons

- **Threads best implemented as a library**
  - But kernel threads not best interface on which to do this
- **Better kernel interfaces have been suggested**
  - See Scheduler Activations [Anderson et al.]
  - Maybe too complex to implement on existing OSes (some have added then removed such features)
- **Standard threads still fine for most purposes**
  - Use kernel threads if I/O concurrency main goal
  - Use $n : m$ threads for highly concurrent (e.g,. scientific applications) with many thread switches
- **But concurrency greatly increases complexity**
  - More on that in concurrency, synchronization lectures…